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Abstract
The work that I'm going to describe was funded by the Air Force Materials Lab from February 1972 to February 1974. It is described in an AFML report, TR- 74-80, available from the Air Force. This report describes a more practical type of problem than has been discussed so far. Our work was directed towards building an ultrasonic system to be used on aircraft in the field to detect cracks around fastener holes with the fastener in place. With this system we are able to detect cracks and locate them relative to the depth of the hole. Estimates of crack size by this method are not very accurate.

Disciplines
Materials Science and Engineering | Structures and Materials

DEVELOPMENT OF A FIELD INSPECTION SYSTEM FOR DETECTION OF CRACKS UNDER INSTALLED FASTENERS

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The work that I'm going to describe was funded by the Air Force Materials Lab from February 1972 to February 1974. It is described in an AFML report, TR-74-80, available from the Air Force. This report describes a more practical type of problem than has been discussed so far. Our work was directed towards building an ultrasonic system to be used on aircraft in the field to detect cracks around fastener holes with the fastener in place. With this system we are able to detect cracks and locate them relative to the depth of the hole. Estimates of crack size by this method are not very accurate.

At present, hole inspection is largely performed by visual or radiographic methods which are only sensitive to rather large cracks around fasteners. Alternatively, the fastener may be removed and an eddy current probe passed into the hole to sense the presence of cracks. There are good reasons for not taking the fastener out if you can avoid it. In the process of removal and replacement, holes are frequently damaged and become in worse condition than before fastener removal. Some of the advantages of ultrasonic methods are listed in Fig. 1. It is not necessary to remove the fastener, you can look at holes more rapidly, and the possible damage to holes by fastener removal and reinstallation is avoided. The ultrasonic method should be a more rapid and less costly inspection technique and, by early crack detection, one can frequently drill out a hole to enlarge it and replace the fastener with a larger fastener and continue to use the structure.

What we are attempting to do is to detect cracks at the locations seen in Fig. 2 at the base of the countersink in flush head fasteners and at the upper and lower surfaces in straight holes. In all cases we are restricted to detection of cracks in the skin layer in which sound is injected. Reference will be made to radial depth and bore length of cracks as seen in the sketch in Fig. 2. Typically, these are about the same dimension for cracks found in aircraft structures. These cracks are detected with conventional shear wave ultrasonic pulse echo techniques.

The specific requirements of our contract, given in Fig. 3, included the use of the shear wave technique. A pilot study by a separate organization, prior to our work on this problem, suggested this was the most likely way to improve the inspection of these holes. We were to automate the technique and to produce a prototype unit which could be taken to the field and demonstrated on operational Air Force aircraft.

ADVANTAGES OF ULTRASONIC METHOD
- NO FASTENER REMOVAL

- INCREASED SURVEILLANCE POSSIBLE – BETTER STRUCTURAL INTEGRITY
- NO DAMAGE TO AND REPAIR OF GOOD HOLES – AS WITH E.C.
- RAPID INSPECTION – LESS COST/HOLE
- EARLY CRACK DETECTION – MIMIMIZES REPAIRS

Fig. 1. Advantages of ultrasonic inspection methods.

GENERAL OBJECTIVE
DETECT HOLE WALL CRACKS WITHOUT FASTENER REMOVAL

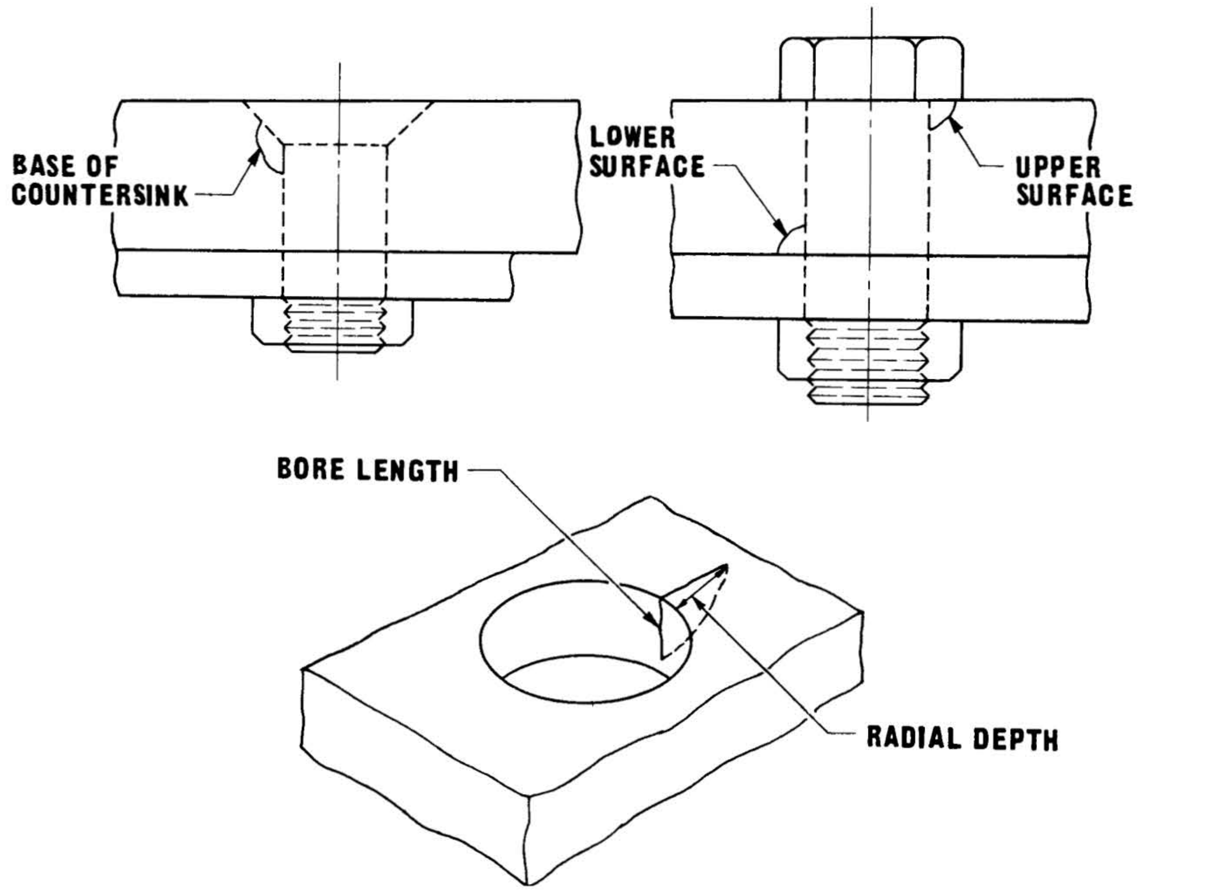


Fig. 2. Geometry of crack flaws in fastener systems.

SPECIFIC REQUIREMENTS

- **UTILIZE ULTRASONIC SHEAR WAVE METHOD**
- **AUTOMATE TECHNIQUE AND PRODUCE PORTABLE PROTOTYPE EQUIPMENT**
- **DEMONSTRATE ON ACTUAL SYSTEMS (B-52, C-5A, KC-135, ETC.)**

Fig. 3. Requirements in Boeing study.

The aircraft selected for the purpose of the contract was the B-52. It has been in service since 1955. I don't know the age distribution of these ships, but there are at least 400 of them still flying and many of them do have crack problems. Air Force personnel at Oklahoma City defined 5 separate arrays of B-52 fasteners with different sized fasteners, hole diameters, face sheet thicknesses, and varying spacing between the fasteners. The range of parameters to be considered is shown in Fig. 4. The 0.6 inch spacing refers to the maximum distance that we could have between the sound entrance point and the center of the fastener being inspected. The fasteners and surrounding metal may be painted and there may be a sealant between the layers held together by the fastener.

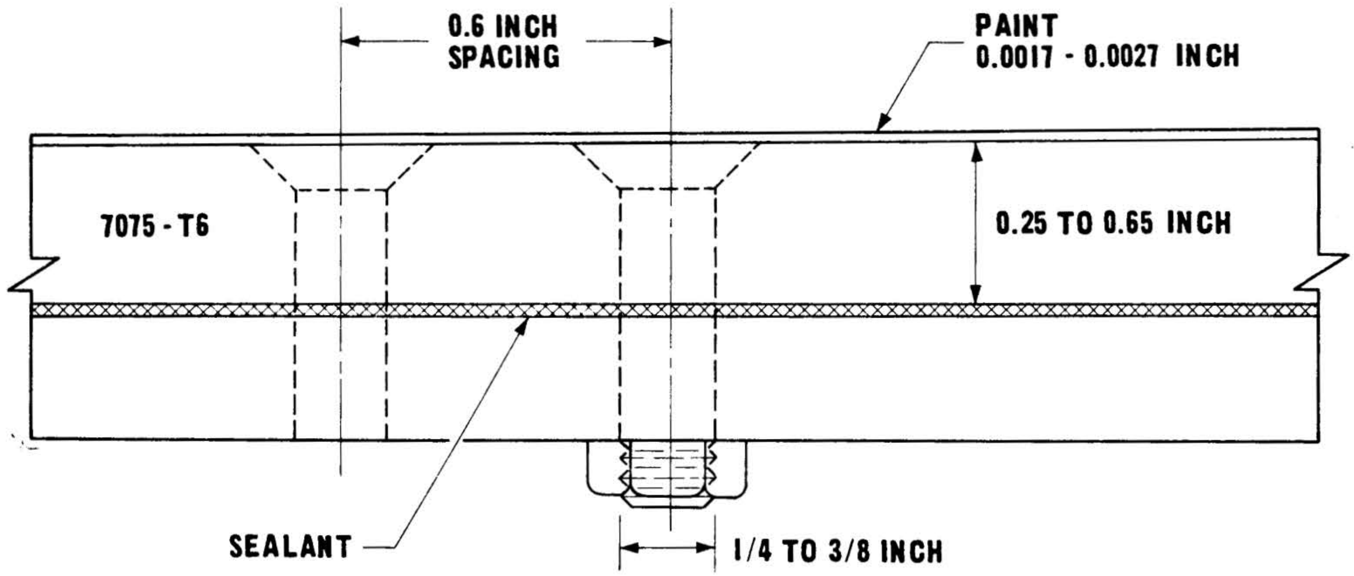
Charles Raatz, in evaluating ultrasonic techniques for this problem used an ultrasonic tank to develop transducer position data for use in designing the scanner to be used in the field. Initially he was working in immersion using transducers directed towards fasteners in plates mounted on a rotating turntable. The fasteners in these test samples were positioned at the center of rotation. The angle of incidence of the transducer could be varied by a manipulator. The transducer could also be moved vertically and along X and Y axis in the plane of the test samples. A second manipulator enabled another transducer to be used for dual transducer investigations.

A large number of specimens were prepared covering the required range of thicknesses and fastener dimensions. Fasteners from 3/16 inch to 1/2 inch were used with face sheets from 0.25 inch to 0.65 inch thick. In order to verify our ability to detect cracks in the locations given in Fig. 2, EDM notches were placed in these test specimens. These enabled comparisons to be made of the sensitivity of various ultrasonic modes that were considered for this problem. Duplication of EDM notches in a given location in different specimens is, of course, much easier than the growth of fatigue cracks.

The sound paths selected for the three possible crack locations are illustrated in Fig. 5. For faying surface cracks, a shear wave was used to reflect from the crack and return along the same path to the receiving transducer. For the base of countersink cracks a rather large refracted angle, 70 degrees, was used to cause the sound to reflect from a crack or notch and return to the transducer. A single transducer shear wave technique was also used for the upper surface cracks. Sound was reflected from the bottom surface of the top layer up to the crack and returned to the transducer along the same path.

With one exception, these techniques were successfully demonstrated on the test specimens containing EDM notches. When the face sheet thickness was greater than 0.42 inch it was not possible to detect upper surface cracks around straight holes. For thicknesses over 0.42 inch the sound entrance point was more than 0.6 inch from the center of the fastener. Due to the limitation on transducer position imposed by the fastener array spacing, moving the sound entrance point more than 0.6 inch from the fastener center was not permitted.

TYPICAL CONDITIONS



INCLUDING: STEEL AND TITANIUM ALLOYS
STRAIGHT AND TAPER SHANK

Fig. 4. Range of parameters treated in the B-52 fastener study.

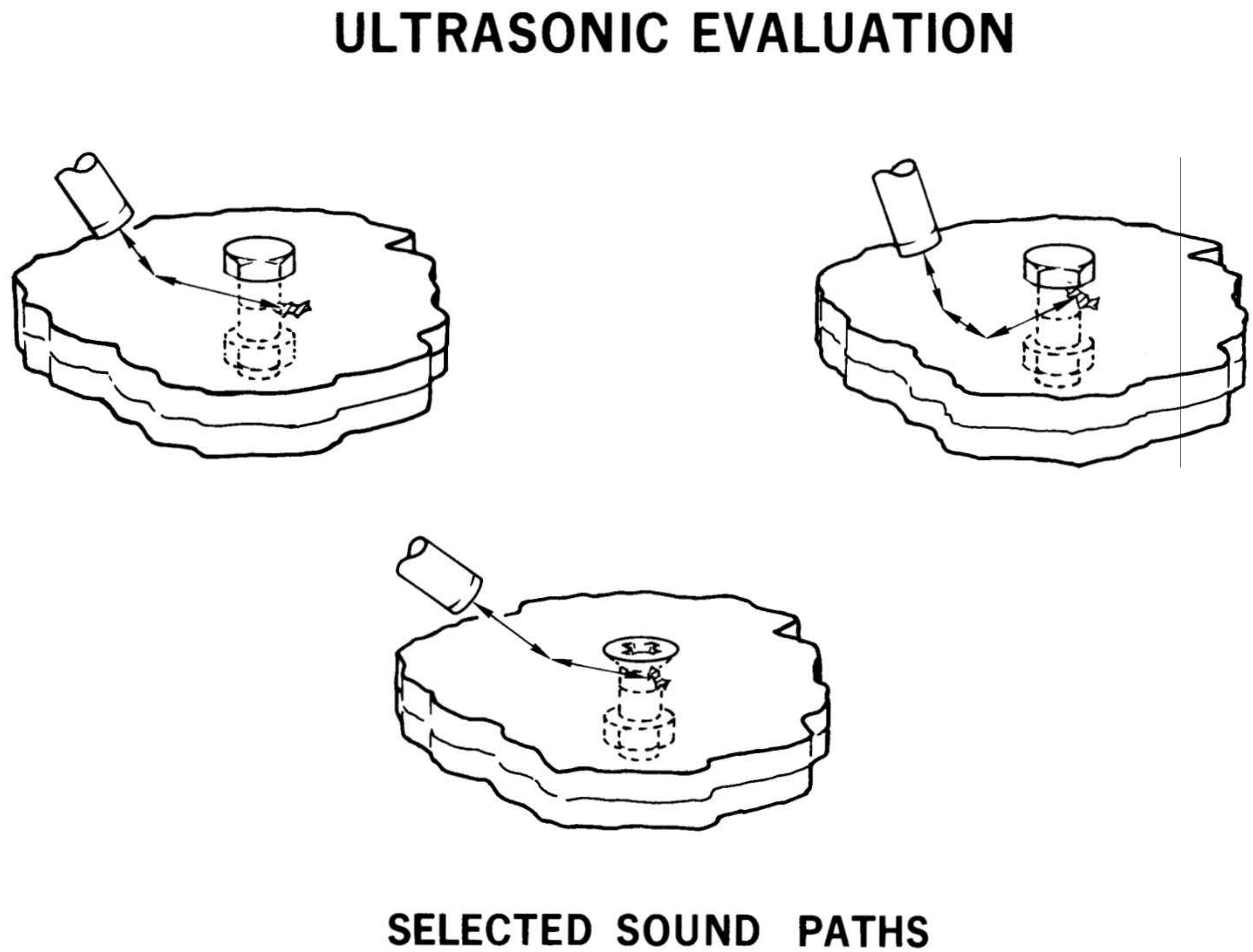


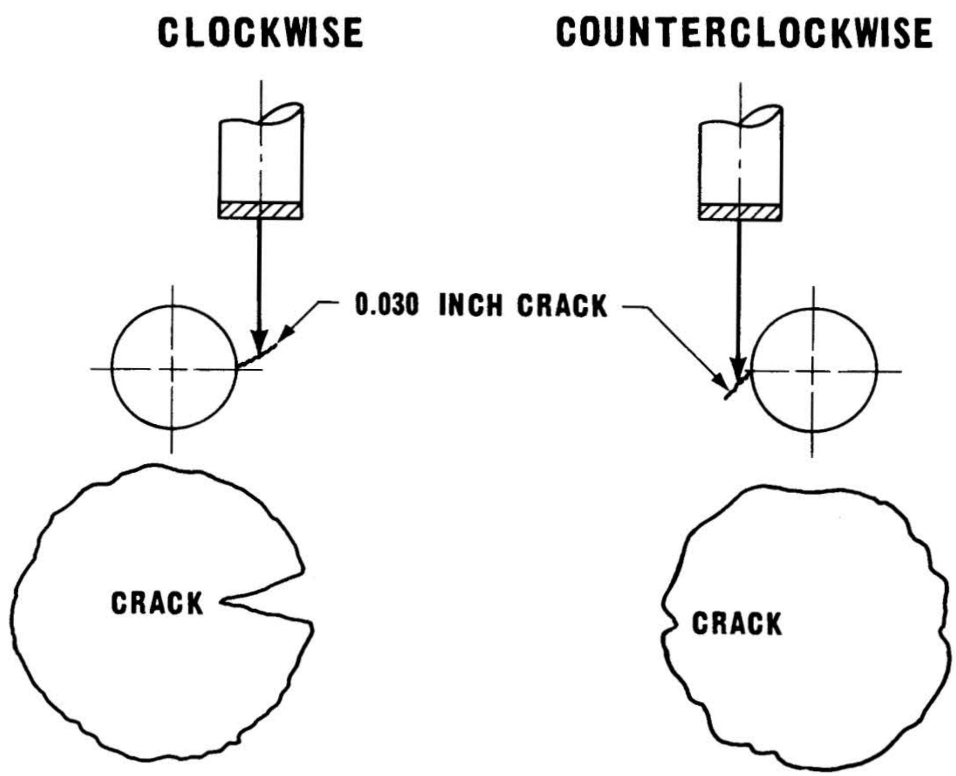
Fig. 5. Sound path geometries used for three different possible crack locations.

In the three different locations considered, the sensitivity that was obtained corresponded to EDM notches with radial depths on the order of 20 mils at the faying surface, 30 mils at the base of the countersink, and 25 mils at the upper surface. This was over the range of fasteners and sheet thicknesses as defined by the B-52 fastener arrays (except as noted in the previous paragraph). About an equal number of specimens were made up with fatigue cracks for more realistic evaluation of the system detection capability. The fatigue cycle used to generate these cracks resulted in very tight fatigue cracks and our ability to detect these was diminished. Another characteristic observed with the fatigue crack samples was that if a given transducer was successively offset to equivalent positions on opposite sides of a fastener hole, the responses to a crack could be quite different for the two offsets as shown in Fig. 6. As cracks do not necessarily grow radially from the holes, the differences in echoes from the two transducer positions was reasonable. Similar behavior was observed when we subsequently worked on the KC-135 and C-5A fatigue aircraft. It was estimated that 30% of the cracks detected on these aircraft showed significant differences in detected signal amplitude with the two offsets. The recommended procedure for hole inspection thus includes separate tests with the transducer offset on both sides of the hole.

A comparison of echo signals from EDM notches and fatigue cracks of similar sizes may be seen in Fig. 7. This represents the amplitude obtained from EDM notches which were 20 by 30 mils and 40 by 30 mils shown as the interrupted lines. The solid lines show the changes in echo amplitude when the test specimens were loaded in tension while monitoring signals reflected from these very tight fatigue cracks. When they were loaded sufficiently, the crack signals agreed reasonably well with the echos for notches of similar size. Fatigue cracks detected on the actual aircraft, however, were not as tightly clamped and echos obtained from them more closely resembled the equivalent size EDM notches than was the case with the laboratory fatigue crack samples. On the aircraft the fatigue processes evidently provide more opportunity for fretting, more chemical action takes place at the crack faces, and the cracks appear to be more open.

Roger Senske, another participant in this program, characterized the transducers that were used through spectral measurements and axial and transverse beam profiles. He looked at a total of 18 transducers. These were 5, 10, and 15 MHz commercial transducers. Over half of these had multiple peaks in their measured spectra as indicated in Fig. 8 and hardly any of them agreed with their nominal frequency. However, in examining the performance of the transducers in responding to the notches and the cracks in our test specimens, we did not see any significant relation between the spectra and crack or notch detection sensitivity. The transducer that was selected for this work is a 10 MHz, 3/16 inch diameter unit, chosen on the basis of its ability to respond to the broadest range of cracks and notches with the best signal to noise ratio.

ULTRASONIC EVALUATION



DIRECTIONAL RESPONSE

Fig. 6. Crack responses showing directional influence as a result of transducer offset on opposite sides of a fastener hole.

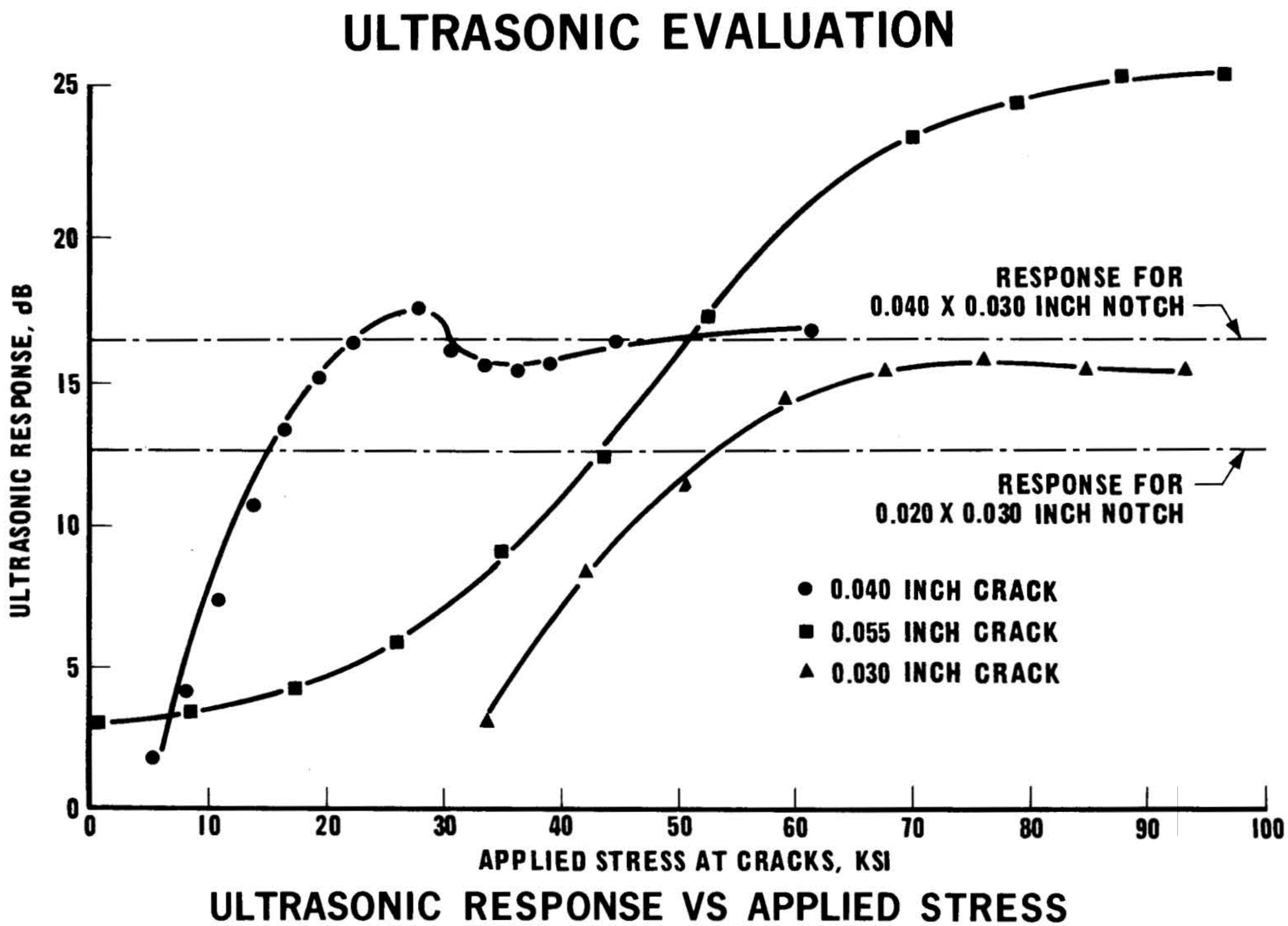
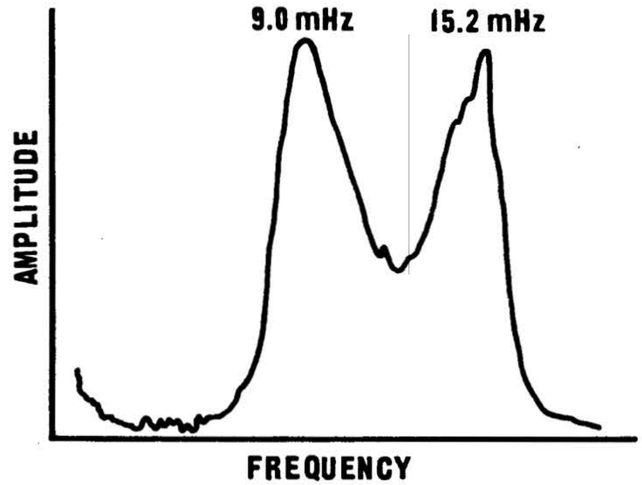
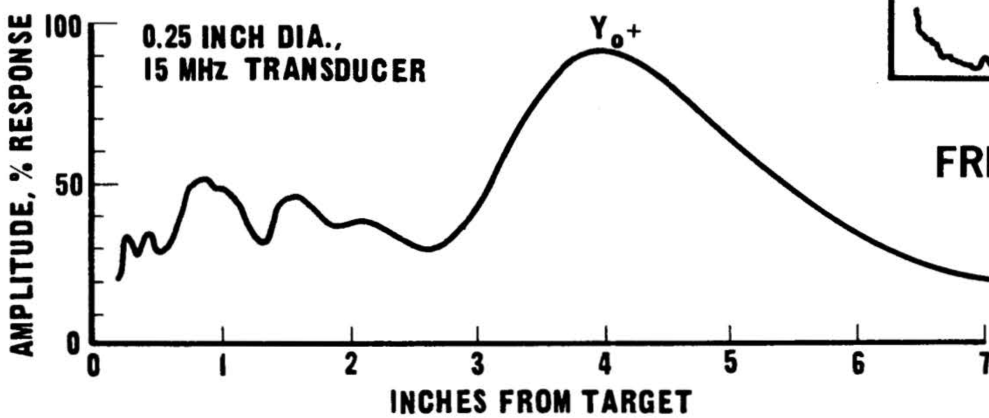


Fig. 7. Ultrasonic response as a function of applied stress for fatigue cracks compared with that for EDM notches.

TRANSDUCER EVALUATION



FREQUENCY SPECTRUM



PROFILE

Fig. 8. Response characteristics of typical commercial transducers.

A notch or crack in the test specimens was considered detected if the transducer could be moved away from its optimum location by 30 mil increments in each of four directions and still yield a signal to noise ratio greater than 2 to 1. This was to simulate improper centering by an operator in a field inspection in which the scanning device must be manually held against an aircraft to perform an inspection.

For our prototype field scanner, a coupling device was developed which fits on the end of the transducer. This contains a one inch column of water closed off with a thin neoprene rubber boot which contacts the test surface to couple sound into the test surface. A thin film of glycerine-water or oil on the test part afforded a very reliable coupling with a very small quantity of liquid on the aircraft. The transducer and coupler may be seen at the bottom of the scanner pictured in Fig. 9. Russ Woodbury designed our prototype field scanner to provide the variety of transducer positions and incident angles required to perform the B-52 fastener hole inspections. The transducer is mounted on a circular element that rotates when driven by a small DC motor or it can be manually turned. The scanner is centered over the fastener by means of a pointer located at the center of the scanner. An encoder built into the rotating element allows the rotational motion of the scanner to be duplicated by our data displays.

The type of displays generated with the system may be seen in Fig. 10. Storage oscilloscopes were used to retain indications from cracks following completion of rotational scans around fasteners. The output from the time gate of a commercial ultrasonic instrument was used to control the radius of these traces. Crack echo signals within the time gate caused a decrease in the analog output which results in an inward deflection proportional to the echo amplitude within the gate interval. An automatic mode was used to control the rotation of the scanner. When the start button was depressed, the storage monitor was erased and the scanner made one rotation of 360° and stopped. If the stored trace contained no crack indications, the operator moved to the next fastener hole. Use was also made of a circular B-scan as shown in Fig. 11. Echo signals caused intensification of the monitor trace along vectors emanating from the center. This display was useful in determining if coupling was maintained as the scanner rotated. If coupling was lost, there was an increase in the amplitude of echos returned from the interface between the boot and the test surface. This brightened a portion of the trace and broadened it substantially. With the B-scan displays we could frequently interpret complex echo patterns from sources such as the edges of face sheets, fasteners, or fastener heads. In the example in Fig. 11, groups of echos were reflected by various paths from the head of a hexagonal fastener. The time shifts associated with crack signals as the scanner rotated about a fastener were also readily seen in the B-scan presentations. The distinctive changes in radii that crack signals exhibited were helpful in identifying cracks and sorting them from other noise echos.

The system that we used for field inspection is seen in Fig. 12. Bill Davis constructed the electronics used to develop the radial and B-scan displays and the control circuitry for the scanner.

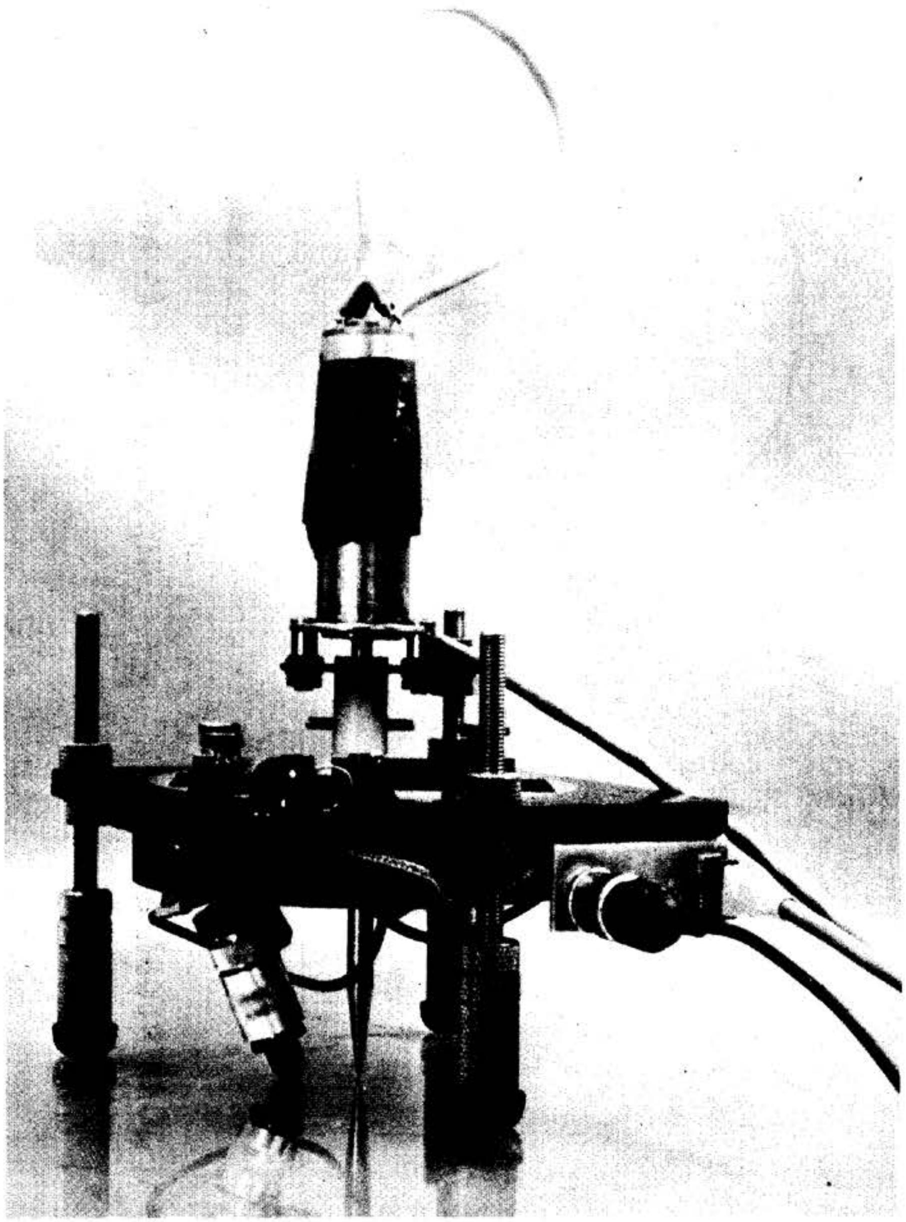


Fig. 9. Photograph of prototype portable field scanner.

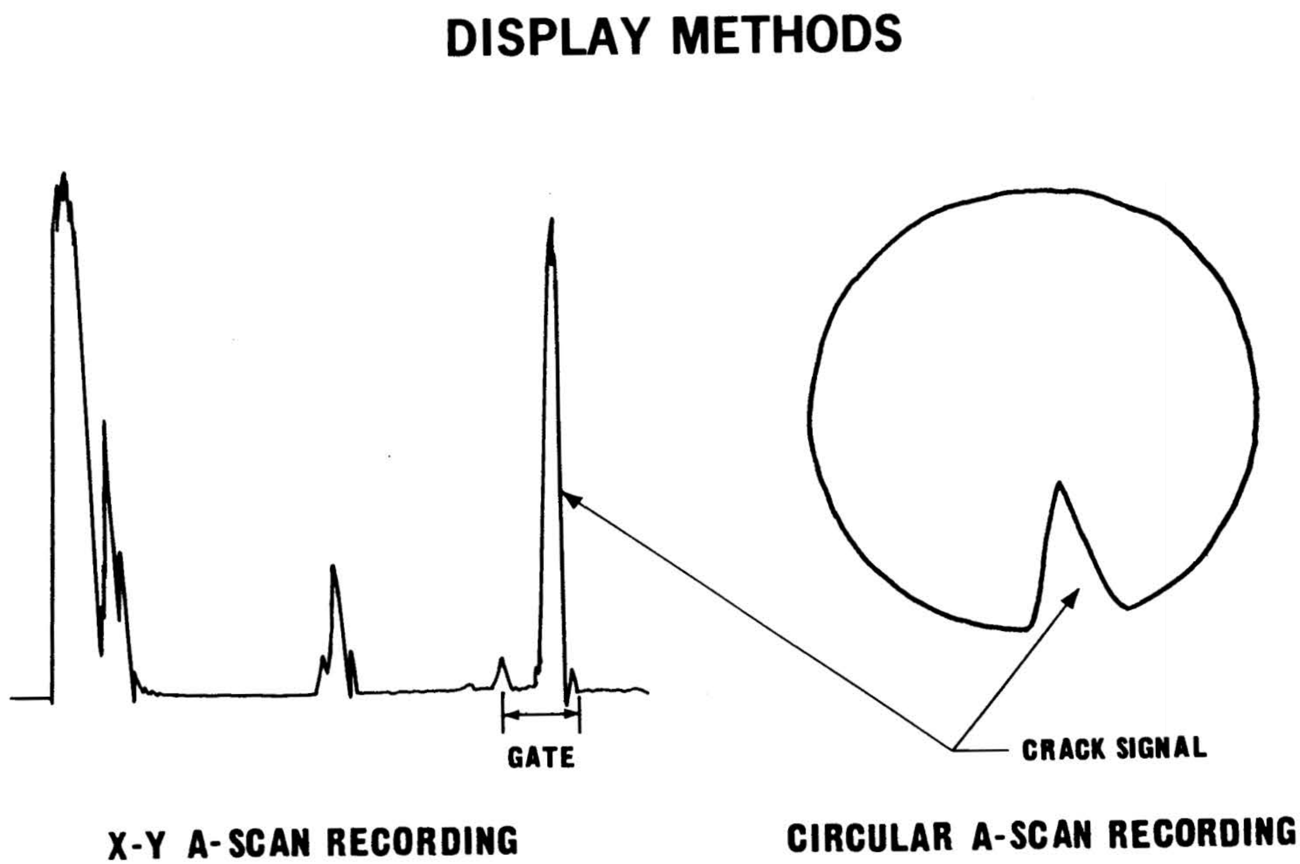
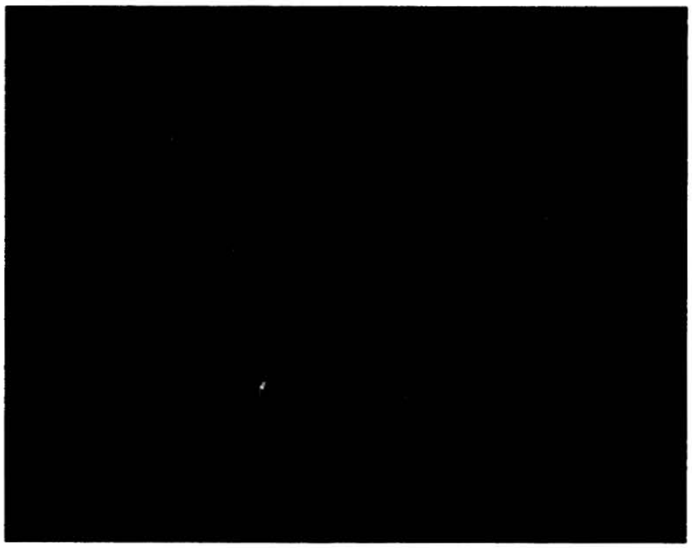


Fig. 10. Typical display generated by field scanner system.

DISPLAY METHODS



CIRCULAR B-SCAN

Fig. 11. Image from circular B-scan system.

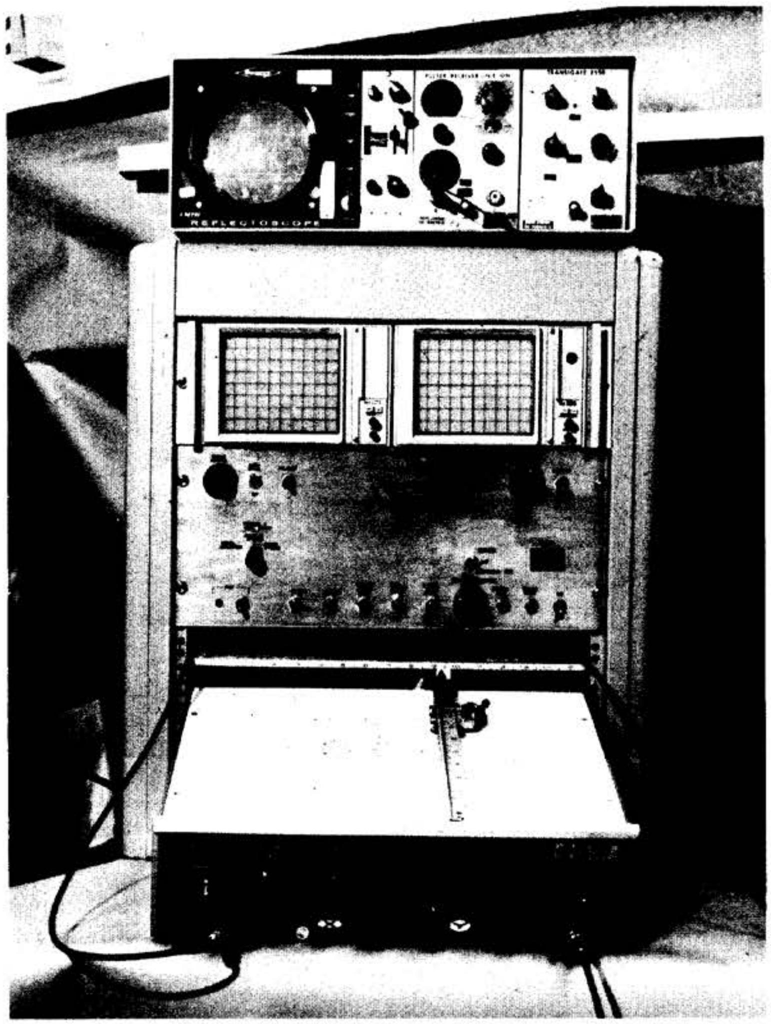


Fig. 12. Photograph of data display console and plotter of the field scanner system.

To evaluate the crack detection system in the field, since the B-52 was not available, tests were performed on 400 fastener holes in the lower wing skins of the KC-135 fatigue aircraft. This plane was used for the fatigue program after having been in service for several thousand hours. It was then brought into a fatigue facility and, at the time we worked on it, it had accumulated the equivalent of 55,000 flight hours. Following our ultrasonic inspection at Wichita, several of the fasteners were cut out of the wing in a single section. This was brought to Renton, Washington where we reexamined the panel with the scanner. We were curious about some holes which had given low level signals we thought might be due to small cracks. At that time, we had had no experience on actual aircraft. We did not know the size of the actual cracks to which we were responding since there were large discrepancies between the signals from our laboratory fatigue crack samples and the EDM notch samples. To determine if these questionable signals in the KC-135 panel were due to tightly closed fatigue cracks, this panel was loaded in a tensile machine while ultrasonically tested to see if the echos were increased as with the lab fatigue samples. No increase in echo signal amplitude was observed. When this panel was subsequently shipped to Dennis Corbley, our AFML monitor, and the holes were sectioned, it was found there were no significant cracks in the holes about which we had been concerned.

The destructive analysis revealed that we had ultrasonically detected among others, three cracks which had radial depths of about 30 mils and approximately the same bore lengths. One crack with a 22 mil radial depth was not detected.

A subsequent test on the C-5A fatigue aircraft yielded similar results. The responses that we obtained from the cracks that we found on the C-5A were comparable to those found on the KC-135. Two cracks were detected that were measured destructively by Lockheed personnel as having, respectively, 28 and 29 mil radial depths. The smallest crack that was missed had a radial depth of about 20 mils.

Our conclusions following the field evaluations are summarized in Fig. 13. In the 660 holes that were examined, cracks with 30 mil or greater radial depths were detected at the lower surface of the outer skin or at the base of countersinks. The rate of inspection was between one and two holes per minute. Considering our evaluations were performed on two aircraft not originally specified in our contract effort, we are confident this system will prove to be a useful field inspection tool for a variety of AF aircraft.

FIELD SYSTEM INSPECTION CAPABILITY

- **ALUMINUM, STEEL, TITANIUM – 0.15 TO 0.75 INCH THICK**
- **STRAIGHT, TAPERSHANK OR COUNTERSUNK HOLES – 3/16 TO 1/2 INCH DIA.**
- **INSPECTION RATE OF 1 TO 2 HOLES/MINUTE**
- **RADIAL DEPTH CRACK DETECTION:**

LOWER SURFACE	BASE OF C/S	UPPER SURFACE
0.030 INCH	0.030 INCH	0.040 INCH (EST.)

Fig. 13. Results of evaluation of field systems inspection capability.

DISCUSSION

DR. BERTONI (Polytechnical Institute of New York): I believe we have time for two questions.

MR. BILL SHELTON (Northrup Corporation): How much more difficult is it to calibrate the instrument when you're trying to detect cracks at the faying surface or the base of the countersink? Is it more difficult to calibrate for that area than it is at the base of the countersink?

MR. WOODMANSEE: The base of the countersink is somewhat more difficult, but it hasn't proved to be all that tough. In our follow-on effort, for example, we will be providing standardizing specimens that contain notches at both of these locations. Since fixed transducer holders will be provided for the fastener diameters and face sheet thicknesses required for the C-5A, the setup procedure will largely be a matter of making gain adjustments to obtain the desired echo amplitudes from the appropriate standards.

DR. BERTONI: One more question?

DR. ADDISON (American Optical): I have a question. I'm not quite sure when you go about inspecting a wing or whatever you inspect, do you do every bolt or do you sample them, or what kind of procedure is outlined for that?

MR. WOODMANSEE: Generally there are regions where cracks have been known to occur either from fatigue aircraft or service experience. Inspections then are generally limited to areas known to have cracking problems.

DR. BERTONI: One more question.

DR. BILL WALKER (AFOSR): In your inspection of your lower wing surfaces were they in situ, that is, attached to the aircraft?

MR. WOODMANSEE: Yes.

DR. WALKER: Or were they off? Then you must have a hand-held operation. What about the pressure sensitivity of your measurement.

MR. WOODMANSEE: That has not been a difficulty. The pressure is borne by the feet on the scanner.

DR. WALKER: Yes, but you're upside down now and gravity is going the other way.

MR. WOODMANSEE: Right, but the transducer coupler, the rubber boot, is slightly deformed by pressing against the surface, and it really hasn't been a problem, upside down, sideways, or from the top. It hasn't been a difficulty.

DR. WALKER: I'd hate to hold it all day long.

MR. WOODMANSEE: It can be tiresome.